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Project Report

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A. S. Friedman

Determination of Specular Reflection
from Cylindrical Satellites
for Electro-optical Surveillance and SOI

8 October 1976

Prepared for the Department of the Air Force
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Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS



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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

A handwritten signature in dark ink, reading "Raymond L. Loiselle". The signature is written in a cursive style with a large, stylized 'R' and 'L'.

Raymond L. Loiselle, Lt. Col., USAF
Chief, ESD Lincoln Laboratory Project Office

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

DETERMINATION OF SPECULAR REFLECTION
FROM CYLINDRICAL SATELLITES
FOR ELECTRO-OPTICAL SURVEILLANCE AND SOI

A. S. FRIEDMAN

Group 94

PROJECT REPORT ETS-3

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ABSTRACT

Although electro-optical satellite surveillance depends primarily upon diffuse solar reflection, an understanding of specular reflection can lead to enhanced detection and identification capability.

An analysis of the timing and duration of observable specular reflections has been completed for the widely applicable case of the cylindrical satellite. A solution is presented for geosynchronous satellites which includes orbital elements and attitude as parameters. This solution, in turn, is broadened to encompass misalignment of spin axis and symmetry axis.

A realization of the above computation in readily accessible, command-structured format has been developed as a planning aid for the GEODSS Experimental Test System. Samples of its output are provided, which record the occurrence of observable specular reflections in a convenient, easily understood calendrical tabulation.

Predicting the timing and duration of observable specular reflections is of considerable interest in the conduct of electro-optical satellite surveillance. Since a satellite may appear many magnitudes brighter when seen by specularly reflected sunlight than when seen only by diffusely reflected sunlight, this interest is quite understandable. Before providing an explanation of this phenomenon, let us turn to an example.

Figure 1 depicts a strip chart segment containing the optical signature (or light curve) of satellite 83525, as observed on 6 May 1976. The horizontal coordinate represents time, here amounting to a span of 90 s, and the vertical coordinate is proportional to satellite brightness. One function of a GEODSS site is the collection of strip charts such as this for further SOI analysis. An examination of the full strip chart reveals that the satellite is performing some sort of periodic gyration, as evidenced by the light curve's period of 40 s.

In order to assign consistent numerical values to brightness measurements, calibration readings of selected stars of known color and brightness must also be taken. [Figure 3]. This procedure provides values for night sky brightness and atmospheric extinction as well.

Figure 2 shows the light curve of the same satellite, this observation made on 25 March 1976. Comparison with Figure 1 reveals an increase in peak brightness of two magnitudes, which can be attributed to specular reflections. In this example the observations are separated by 42 days, but such an effect could arise in the space of 42 hours or 42 minutes.

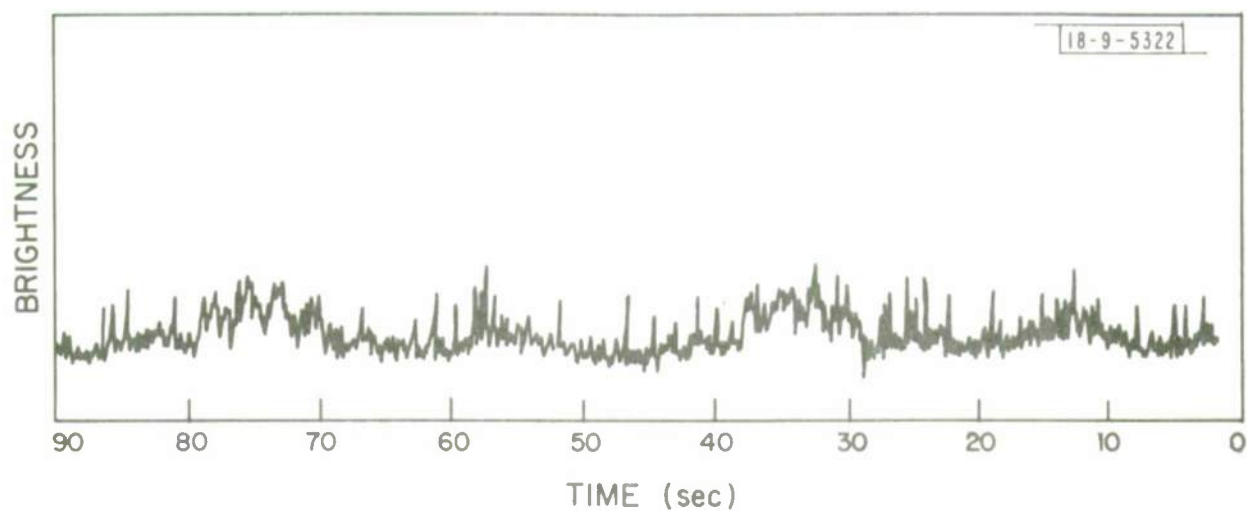


Fig. 1. Light curve of satellite, 83525 6 May 1976

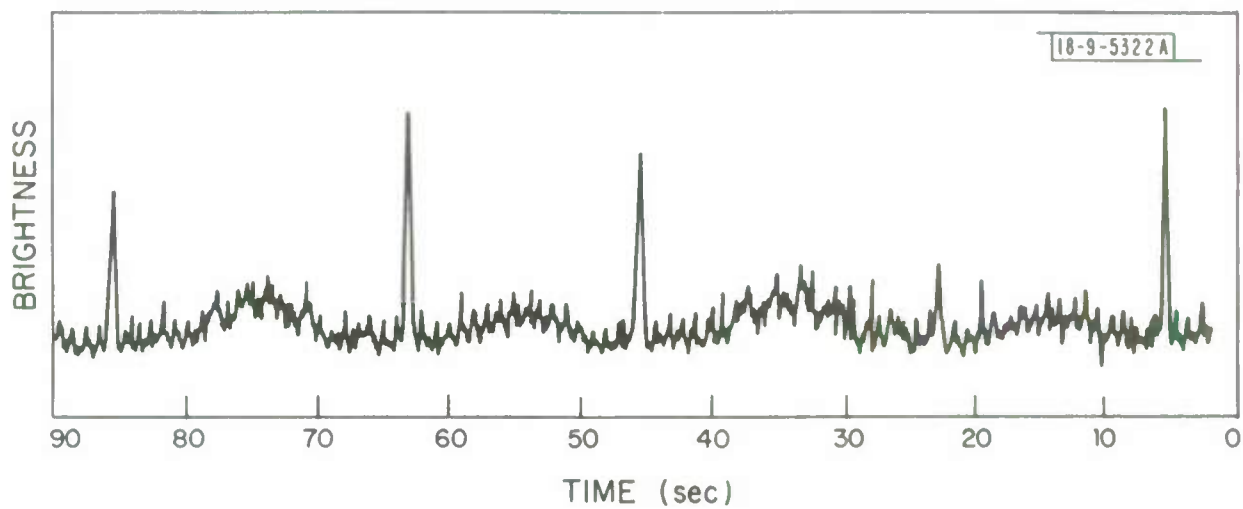


Fig. 2. Light curve of satellite, 83525 25 March 1976

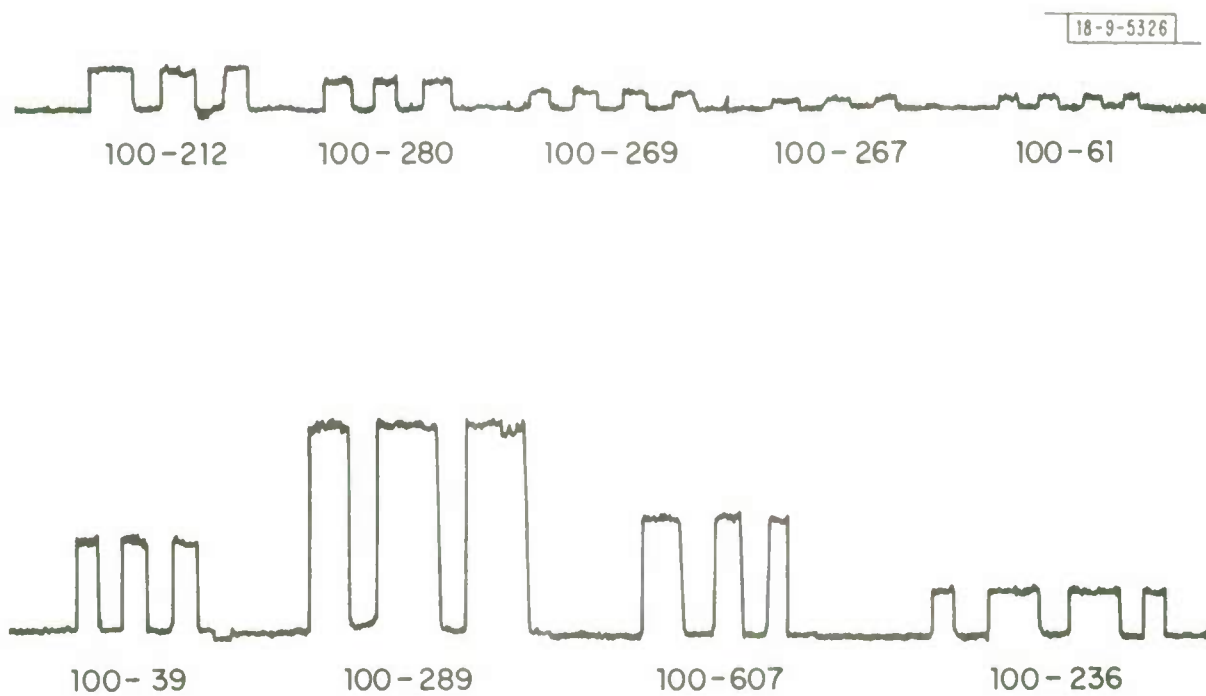


Fig. 3. Light curves, selected Landolt calibration stars

The mission of GEODSS does not include an SOI analysis of the fine structure of light curves, which is the domain of several other Air Force sponsored programs. But a preliminary examination of the light curve for such information as period and average brightness can vitally assist the surveillance role of GEODSS, by confirming the acquisition of a familiar satellite or by providing a means of distinguishing between satellites in the same vicinity. For this reason it is important to understand any phenomenon resulting in an anomalous change in brightness. Furthermore, a mastery of the timing of specular reflections can be a valuable scheduling asset, since maximum brightness should permit minimum search time. An extreme illustration is the case of satellite IMP-6, which was detected electro-optically on 24 October 1973 at a distance of 170,000 km - four times geosynchronous altitude - through the 31-inch telescope at Lowell Observatory. Had specular flashes not been visible, the satellite could not have been seen at all.

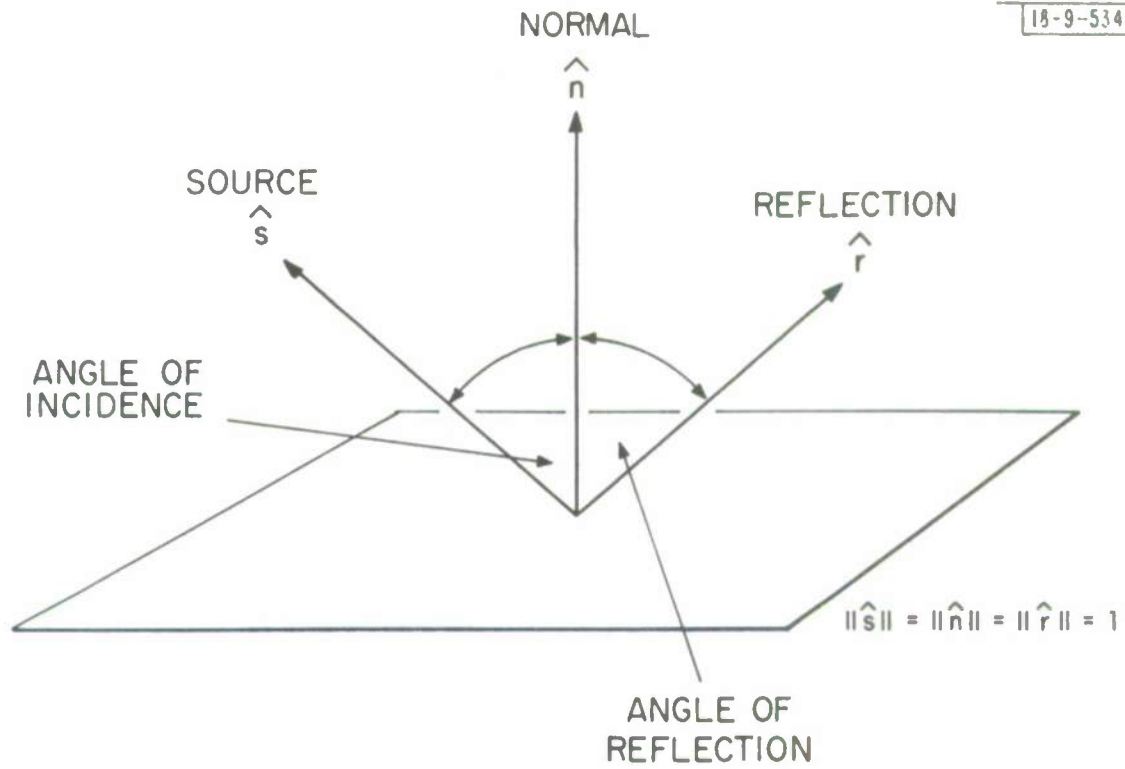
After so many repetitions of the term specular reflection, an explanation is now in order. Mirrorlike reflection from a shiny surface is termed specular, as distinguished from so-called diffuse reflection from an unpolished surface. Diffuse reflection is omnidirectional, while specular is limited in extent and consequently more concentrated. A single object may produce reflections of both types. With respect to satellites, it is diffusely reflected sunlight which ordinarily permits optical detection. Specular reflections, even if they occur, will be visible at a particular terrestrial location only when applicable geometric conditions are satisfied.

For a flat plate, the rule describing specular reflection is well-known: the angle of incidence equals the angle of reflection. This law is depicted in vectorial form in Figure 4. It may be readily extended to curved surfaces by measuring all angles from the normal at the point of reflection.

The chart in Figure 5 describes the current deployment of geosynchronous satellites launched before 1 January 1976. Observe that the large majority have cylindrical bodies. Such satellites are usually faced with solar cells, which are known to be specular reflectors, and for these a specularly reflecting cylinder serves as a good mathematical model. We will limit our attention to this important category, diagrammed in Figure 6. Light rays incident upon the cylinder from a single direction diverge, after reflection, in a multidirectional configuration whose shape is approximately conical. As seen from a sufficiently great distance, that configuration can be regarded as a perfect right circular cone, coaxial with the cylinder and making the same angle with its axis as does the incoming light. [Figure 7].

In the case of solar illumination, the sun may be considered a remote disk of angular diameter one-half degree. Its reflected light thus constitutes a "thickened" cone, of angular thickness one-half degree, as illustrated in Figure 8. Let us now inquire how these reflections impinge upon the earth.

As a preliminary simplification, Figure 9 depicts a spherical earth and an ideal geosynchronous satellite, cylinder axis parallel to the



$$\hat{r} = -\hat{s} + 2(\hat{s} \cdot \hat{n})\hat{n}$$

Fig. 4. Specular reflection from a flat plate-vector representation

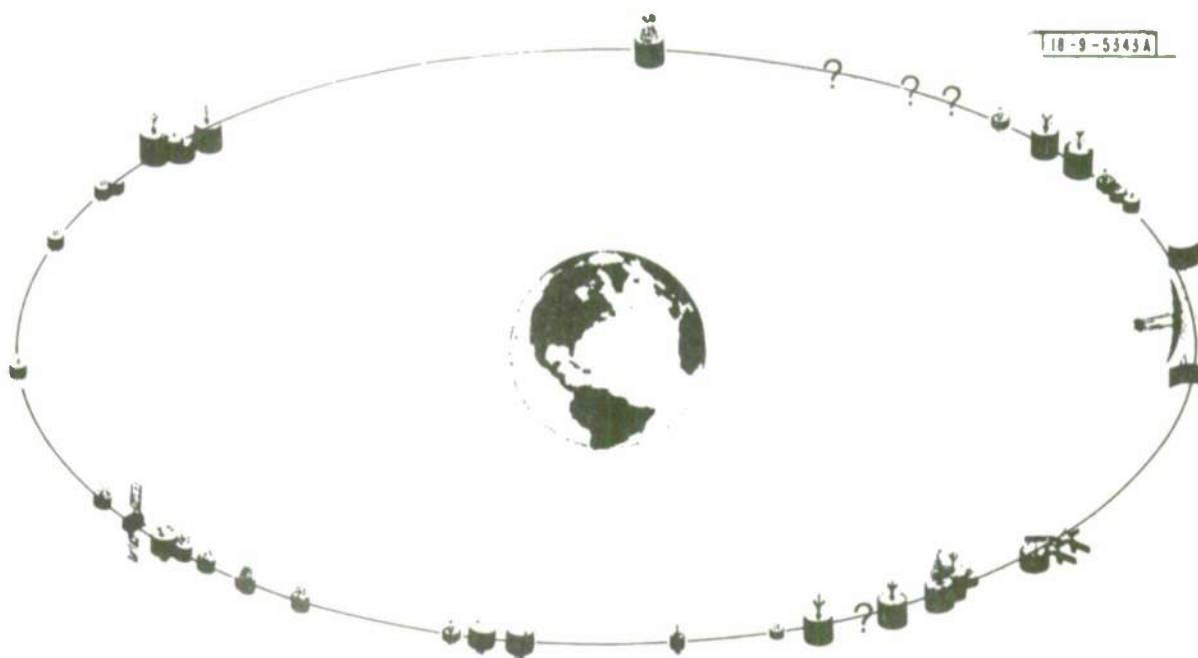
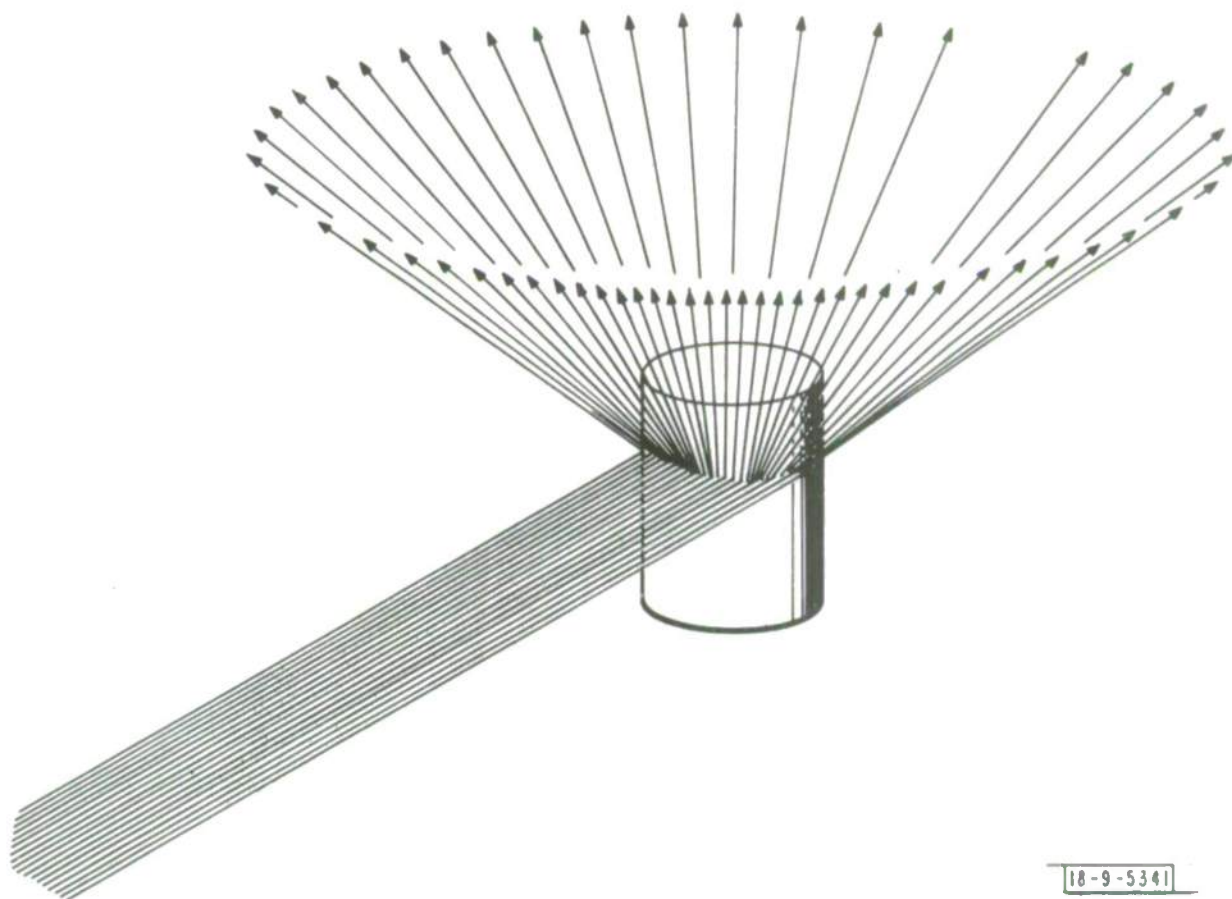


Fig. 5. Geosynchronous satellites launched before 1 January 1976
[Adapted from Comsat Technical Review, vol. 6, no. 1, pp. 196-197]



18-9-5341

Fig. 6. Specular reflection from a cylinder (close up view)



Fig. 7. Specular reflection from a cylinder

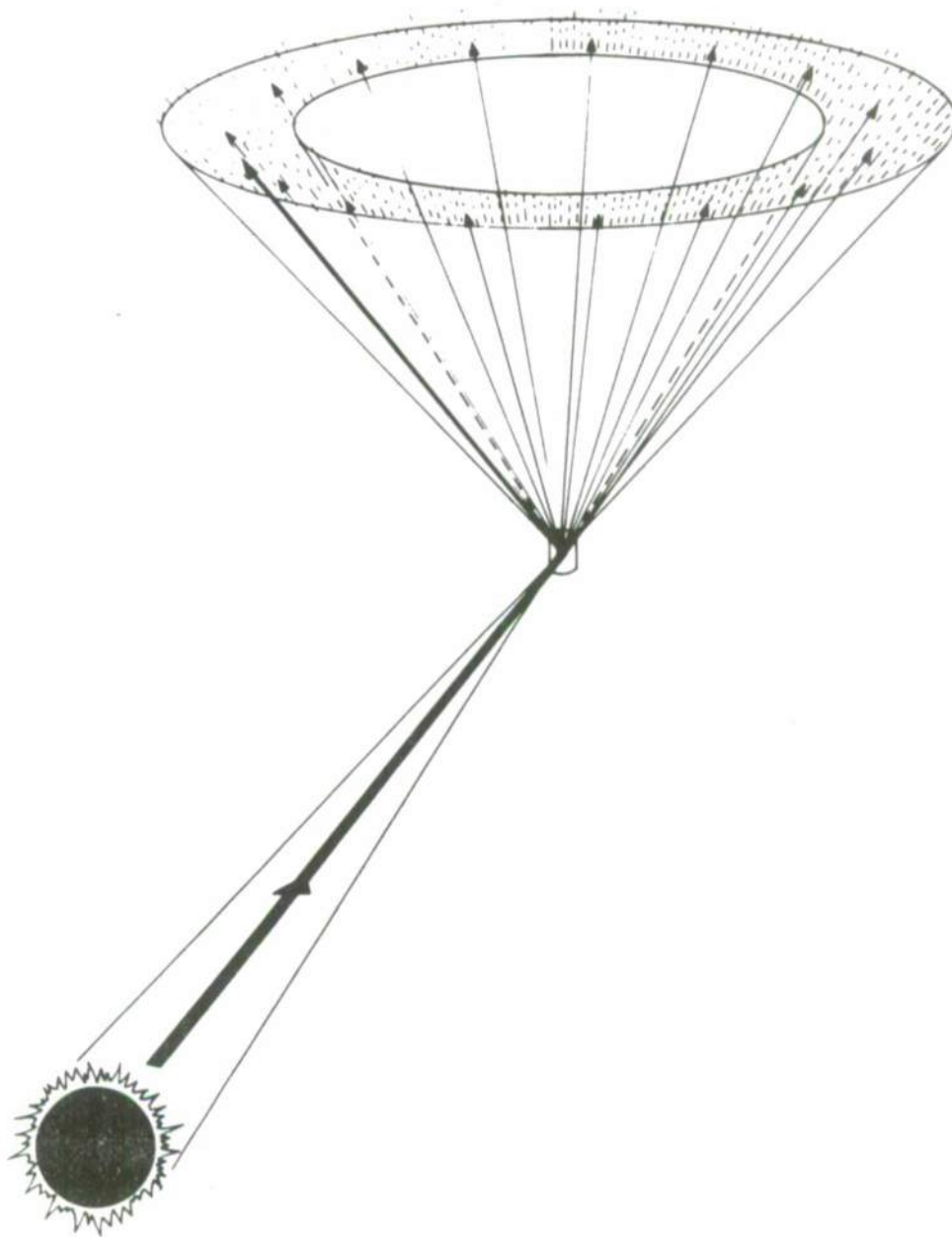


Fig. 8. Solar specular reflection from a cylinder (not to scale)

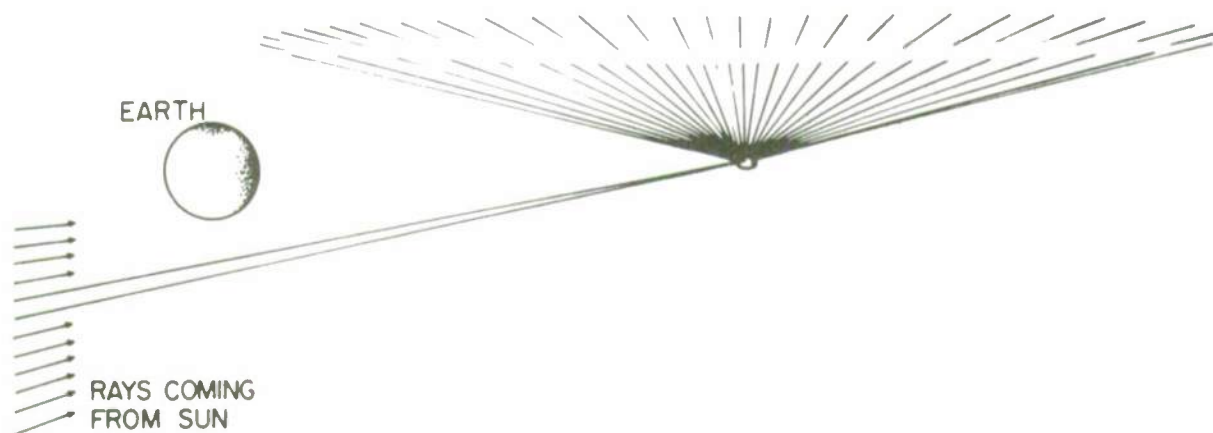


Fig. 9. Terrestrial visibility of solar specular reflection (unfavorable solar declination)

earth's. The sun's declination is such that no specularly reflected rays reach the terrestrial observer. In Figure 10, however, the opposite case is shown, only the rays striking the earth being included. According to the indicated trigonometric relationships, specular reflections are observable at a site of latitude ϕ and sub-satellite longitude if and only if the declination of the source, δ , satisfies the following equation:

$$\tan \delta = \frac{\sin \phi}{\cos \phi - (R_s/R_e)} \quad , \quad (A)$$

where $R_s \approx 42,164$ km is geosynchronous distance, $R_e \approx 6,378$ km is the earth's radius, and hence $(R_s/R_e) \approx 6.61$. Since the source may be any location on the sun's disk, equation (A) is equivalent to the following constraint on solar declination, δ_\odot :

$$\left| \delta_\odot - \arctan \left(\frac{\sin \phi}{\cos \phi - 6.61} \right) \right| \leq 0.5^\circ. \quad (B)$$

Hence, specular reflections are observable at just those times when δ_\odot assumes values in a specific interval, functionally related to site latitude.

The cyclic variation of solar declination is an aspect of the annual course of the seasons, as shown in Figure 11. As a result, each value of solar declination corresponds to two dates. When ϕ is restricted to northern temperate latitudes, for example, the limitations on δ_\odot imposed by equation (B) are seen to confine specular observability

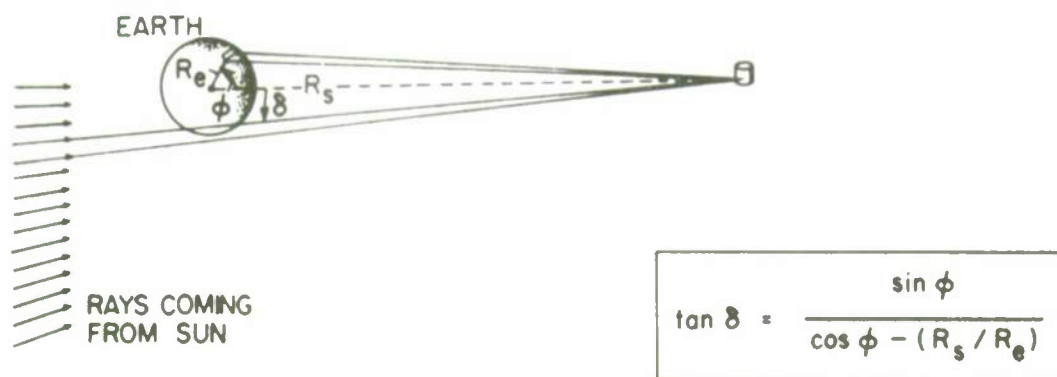


Fig. 10. Terrestrial visibility of solar specular reflection (favorable solar declination)

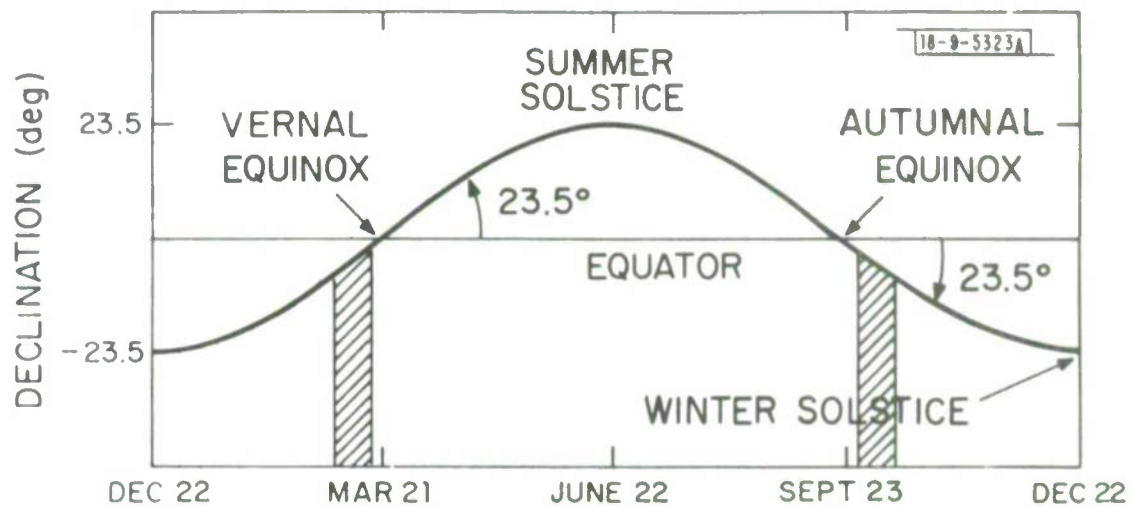


Fig. 11. Annual cycle of solar declination

to one period shortly before the vernal equinox and another shortly after the autumnal, each lasting less than two weeks. The mean rate of change of δ_{\odot} then being about $.38^{\circ}/\text{day}$, the duration of specular observability at any individual site will be approximately 32 hours, part of which will occur during daylight.

Although in the real world the above simplifying assumptions do not hold, the following valid conclusion can be drawn: at a north temperate zone site (such as the Lincoln Laboratory GEODSS Test Site), specular reflections will be prevalent around the time of the equinoxes, particularly before the vernal and after the autumnal. As a corollary, if system detection capability is to be tested under least favorable brightness conditions, sensitivity measurements should be taken near the summer solstice.

A more accurate model of specular timing must take account of all deviations of the satellite orbital elements from true geosynchronous. Likewise, variations in spin axis orientation (also called attitude) must be considered. Satellites which are not perfectly balanced may in addition seem to wobble, as shown in Figure 12. This motion represents a misalignment of the cylinder's spin axis and symmetry axis, which can significantly lengthen the specular viewing period.

The above computational requirements can best be satisfied by a computer program. If it is to serve as a practical planning tool, it must be readily accessible at each GEODSS site, and its results must be provided in a convenient format. The author has written such a program

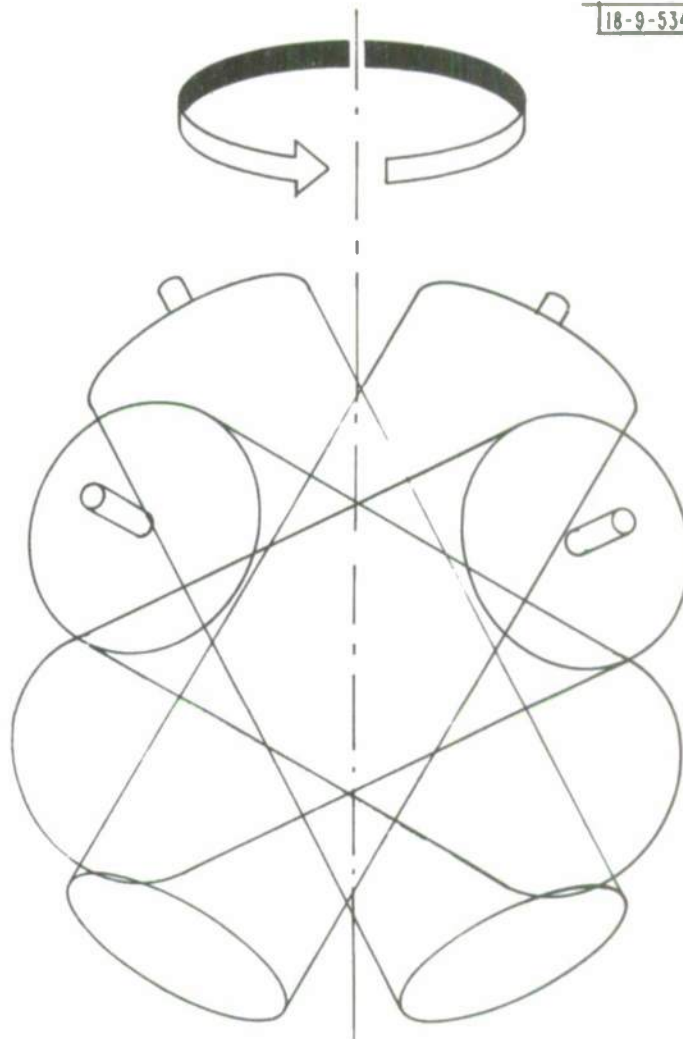


Fig. 12. Wobbling cylinder (spin axis and symmetry axis misaligned)

for the MODCOMP IV minicomputer, an example of whose output is shown in Figure 13. It takes the form of a graphic table, each row representing an observing night, each column an observing time, at ten minute intervals. In addition to observable specular reflections, indicated by (*), the chart specifies the following phenomena: sunset/sunrise (S), twilight (T), eclipse by earth (E), and (for satellites with strong sublongitude drift) descent below horizon (X). The program is interactive and command structured. The computation of a month's specular reflections takes under a minute.

The chart in Figure 13 refers to the true geosynchronous case described above, as seen from a site of latitude 35° and longitude 0° . Figures 14-16 illustrate timing changes resulting from the alteration of a single parameter. The respective modifications are: site moved to latitude 25° ; orbital inclination of 0.5° introduced; axial offset of 0.2° introduced.

When the orbital elements or other parameters are not known exactly, the specular predictions will also contain uncertainty. For example, a change of 0.1° in inclination may cause a shift of as much as six hours in specular observability, and a like change in attitude may have a 12 hour response. When the objective is to recognize a satellite by its known diffuse return, a reasonable precaution is to augment the predicted specular period by a buffer period incorporating recognized uncertainty. When the objective is to capitalize on specular brightness for detection, one should schedule observations near the center of the longest specular

-9-5425

SATELLITE GRAPHIC TIME TABLE
FROM SEP 1976 THROUGH NOV 1976

S=SUNSLT/SUNNR18C
I=TWILIGHT
*SPECIAL REFLECTION 61 SITE
ECLIPSED BY EARTH
LATITUDE LESS THAN 5 DEG

19

SATELLITE SHAPING TIME TABLE
FROM SEP 1975 THROUGH NOV 1978

LOCAL MEAN SOLAR TIME																	
	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8
•1976•																	•1976•
1 SEP 250			1	1	1							1	1	1	1	1	2 SEP 256
2 SEP 250			1	1	1							1	1	1	1	1	3 SEP 257
3 SEP 251			1	1	1							1	1	1	1	1	4 SEP 258
4 SEP 251			1	1	1							1	1	1	1	1	5 SEP 259
5 SEP 251			1	1	1							1	1	1	1	1	6 SEP 259
6 SEP 251			1	1	1							1	1	1	1	1	7 SEP 251
7 SEP 251			1	1	1							1	1	1	1	1	8 SEP 252
8 SEP 251			1	1	1							1	1	1	1	1	9 SEP 253
9 SEP 251			1	1	1							1	1	1	1	1	10 SEP 254
10 SEP 251			1	1	1							1	1	1	1	1	11 SEP 255
11 SEP 251			1	1	1							1	1	1	1	1	12 SEP 256
12 SEP 251			1	1	1							1	1	1	1	1	13 SEP 257
13 SEP 257			1	1	1							1	1	1	1	1	14 SEP 258
14 SEP 258			1	1	1							1	1	1	1	1	15 SEP 259
15 SEP 259			1	1	1							1	1	1	1	1	16 SEP 260
16 SEP 260			1	1	1							1	1	1	1	1	17 SEP 261
17 SEP 261			1	1	1							1	1	1	1	1	18 SEP 262
18 SEP 261			1	1	1							1	1	1	1	1	19 SEP 263
19 SEP 263			1	1	1							1	1	1	1	1	20 SEP 264
20 SEP 264			1	1	1							1	1	1	1	1	21 SEP 265
21 SEP 265			1	1	1							1	1	1	1	1	22 SEP 266
22 SEP 266			1	1	1							1	1	1	1	1	23 SEP 267
23 SEP 267			1	1	1							1	1	1	1	1	24 SEP 268
24 SEP 269			1	1	1							1	1	1	1	1	25 SEP 269
25 SEP 269			1	1	1							1	1	1	1	1	26 SEP 270
26 SEP 270			1	1	1							1	1	1	1	1	27 SEP 271
27 SEP 271			1	1	1							1	1	1	1	1	28 SEP 272
28 SEP 272			1	1	1							1	1	1	1	1	29 SEP 273
29 SEP 273			1	1	1							1	1	1	1	1	30 SEP 274
30 SEP 274			1	1	1							1	1	1	1	1	1 OCT 275
•1976•																	•1976•
1 OCT 275			1	1	1							1	1	1	1	1	2 OCT 276
2 OCT 276			1	1	1							1	1	1	1	1	3 OCT 277
3 OCT 277			1	1	1							1	1	1	1	1	4 OCT 278
4 OCT 278			1	1	1							1	1	1	1	1	5 OCT 279
5 OCT 279			1	1	1							1	1	1	1	1	6 OCT 280
6 OCT 280			1	1	1							1	1	1	1	1	7 OCT 281
7 OCT 281			1	1	1							1	1	1	1	1	8 OCT 282
8 OCT 282			1	1	1							1	1	1	1	1	9 OCT 283
9 OCT 283			1	1	1							1	1	1	1	1	10 OCT 284
10 OCT 284			1	1	1							1	1	1	1	1	11 OCT 285
11 OCT 285			1	1	1							1	1	1	1	1	12 OCT 286
12 OCT 286			1	1	1							1	1	1	1	1	13 OCT 287
13 OCT 287			1	1	1							1	1	1	1	1	14 OCT 288
14 OCT 288			1	1	1							1	1	1	1	1	15 OCT 289
15 OCT 289			1	1	1							1	1	1	1	1	16 OCT 290
16 OCT 290			1	1	1							1	1	1	1	1	17 OCT 291
17 OCT 291			1	1	1							1	1	1	1	1	18 OCT 292
18 OCT 292			1	1	1							1	1	1	1	1	19 OCT 293
19 OCT 293			1	1	1							1	1	1	1	1	20 OCT 294
20 OCT 294			1	1	1							1	1	1	1	1	21 OCT 295
21 OCT 295			1	1	1							1	1	1	1	1	22 OCT 296
22 OCT 296			1	1	1							1	1	1	1	1	23 OCT 297
23 OCT 297			1	1	1							1	1	1	1	1	24 OCT 298
24 OCT 298			1	1	1							1	1	1	1	1	25 OCT 299
25 OCT 299			1	1	1							1	1	1	1	1	26 OCT 300
26 OCT 300			1	1	1							1	1	1	1	1	27 OCT 301
27 OCT 301			1	1	1							1	1	1	1	1	28 OCT 302
28 OCT 302			1	1	1							1	1	1	1	1	29 OCT 303
29 OCT 303			1	1	1							1	1	1	1	1	30 OCT 304
30 OCT 304			1	1	1							1	1	1	1	1	1 NOV 305
1 NOV 305			1	1	1							1	1	1	1	1	2 NOV 306
•1976•																	•1976•
1 NOV 306			1	1	1							1	1	1	1	1	2 NOV 307
2 NOV 307			1	1	1							1	1	1	1	1	3 NOV 308
3 NOV 308			1	1	1							1	1	1	1	1	4 NOV 309
4 NOV 309			1	1	1							1	1	1	1	1	5 NOV 310
5 NOV 310			1	1	1							1	1	1	1	1	6 NOV 311
6 NOV 311			1	1	1							1	1	1	1	1	7 NOV 312
7 NOV 312			1	1	1							1	1	1	1	1	8 NOV 313
8 NOV 313			1	1	1							1	1	1	1	1	9 NOV 314
9 NOV 314			1	1	1							1	1	1	1	1	10 NOV 315
10 NOV 315			1	1	1							1	1	1	1	1	11 NOV 316
11 NOV 316			1	1	1							1	1	1	1	1	12 NOV 317
12 NOV 317			1	1	1							1	1	1	1	1	13 NOV 318
13 NOV 318			1	1	1							1	1	1	1	1	14 NOV 319
14 NOV 319			1	1	1							1	1	1	1	1	15 NOV 320
15 NOV 320			1	1	1							1	1	1	1	1	16 NOV 321
16 NOV 321			1	1	1							1	1	1	1	1	17 NOV 322
17 NOV 322			1	1	1							1	1	1	1	1	18 NOV 323
18 NOV 323			1	1	1							1	1	1	1	1	19 NOV 324
19 NOV 324			1	1	1							1	1	1	1	1	20 NOV 325
20 NOV 325			1	1	1							1	1	1	1	1	21 NOV 326
21 NOV 326			1	1	1							1	1	1	1	1	22 NOV 327
22 NOV 327			1	1	1							1	1	1	1	1	23 NOV 328
23 NOV 328			1	1	1							1	1	1	1	1	24 NOV 329
24 NOV 329			1	1	1							1	1	1	1	1	25 NOV 330
25 NOV 330			1	1	1							1	1	1	1	1	26 NOV 331
26 NOV 331			1	1	1							1	1	1	1	1	27 NOV 332
27 NOV 332			1	1	1							1	1	1	1	1	28 NOV 333
28 NOV 333			1	1	1							1	1	1	1	1	29 NOV 334
29 NOV 334			1	1	1							1	1	1	1	1	30 NOV 335
30 NOV 335			1	1	1							1	1	1	1	1	1 DEC 336
1 DEC 336			1	1	1							1	1	1	1	1	2 DEC 337

S=SUMSAT/SUMPRISZ
TOTW16M1
O=SPECULAN REFLECTION AT SITE
E=ECLIPSEU BY EARTH
Z=ALTITUDE LESS THAN 0 MCG

Fig. 14. Specular reflection visibility chart (change in site latitude of 10^0)

SPECULAR REFLECTION FROM CYLINDRICAL SATELLITE, SPIN AXIS = SYMMETRY AXIS
 (U.S.S.R.) SITE: LAOS
 U.S.S.R. HYPERMETRIC SEUSALMAGNUS SATELLITE

9-5423

ELUPE 1974 200 01 01 0.00 20 0.000000 10 5.5353
 NO 1.000000 00 0.000000 00 0.000000 00 0.000000
 ANGLE 90.0000 0.0000 0.0000 0.0000
 HOURS 1.00 0.00 0.00 0.00
 OFFSET FROM U.S.S.R. 0.00 0.00 0.00 0.00

SATELLITE GRAPHIC TIME TABLE
 FROM SEP 1975 THROUGH NOV 1975

		LOCAL MEAN SOLAR TIME													
		10	11	12	13	14	15	16	17	18	19	20	21	22	23
1 SEP 1975	1 01 00														2 SEP 245
2 SEP 1975	1 01 00														3 SEP 246
3 SEP 1975	1 01 00														4 SEP 247
4 SEP 1975	1 01 00														5 SEP 248
5 SEP 1975	1 01 00														6 SEP 249
6 SEP 1975	1 01 00														7 SEP 250
7 SEP 1975	1 01 00														8 SEP 251
8 SEP 1975	1 01 00														9 SEP 252
9 SEP 1975	1 01 00														10 SEP 253
10 SEP 1975	1 01 00														11 SEP 254
11 SEP 1975	1 01 00														12 SEP 255
12 SEP 1975	1 01 00														13 SEP 256
13 SEP 1975	1 01 00														14 SEP 257
14 SEP 1975	1 01 00														15 SEP 258
15 SEP 1975	1 01 00														16 SEP 259
16 SEP 1975	1 01 00														17 SEP 260
17 SEP 1975	1 01 00														18 SEP 261
18 SEP 1975	1 01 00														19 SEP 262
19 SEP 1975	1 01 00														20 SEP 263
20 SEP 1975	1 01 00														21 SEP 264
21 SEP 1975	1 01 00														22 SEP 265
22 SEP 1975	1 01 00														23 SEP 266
23 SEP 1975	1 01 00														24 SEP 267
24 SEP 1975	1 01 00														25 SEP 268
25 SEP 1975	1 01 00														26 SEP 269
26 SEP 1975	1 01 00														27 SEP 270
27 SEP 1975	1 01 00														28 SEP 271
28 SEP 1975	1 01 00														29 SEP 272
29 SEP 1975	1 01 00														30 SEP 273
30 SEP 1975	1 01 00														1 OCT 274
1 OCT 1975	1 01 00														2 OCT 275
2 OCT 1975	1 01 00														3 OCT 276
3 OCT 1975	1 01 00														4 OCT 277
4 OCT 1975	1 01 00														5 OCT 278
5 OCT 1975	1 01 00														6 OCT 279
6 OCT 1975	1 01 00														7 OCT 280
7 OCT 1975	1 01 00														8 OCT 281
8 OCT 1975	1 01 00														9 OCT 282
9 OCT 1975	1 01 00														10 OCT 283
10 OCT 1975	1 01 00														11 OCT 284
11 OCT 1975	1 01 00														12 OCT 285
12 OCT 1975	1 01 00														13 OCT 286
13 OCT 1975	1 01 00														14 OCT 287
14 OCT 1975	1 01 00														15 OCT 288
15 OCT 1975	1 01 00														16 OCT 289
16 OCT 1975	1 01 00														17 OCT 290
17 OCT 1975	1 01 00														18 OCT 291
18 OCT 1975	1 01 00														19 OCT 292
19 OCT 1975	1 01 00														20 OCT 293
20 OCT 1975	1 01 00														21 OCT 294
21 OCT 1975	1 01 00														22 OCT 295
22 OCT 1975	1 01 00														23 OCT 296
23 OCT 1975	1 01 00														24 OCT 297
24 OCT 1975	1 01 00														25 OCT 298
25 OCT 1975	1 01 00														26 OCT 299
26 OCT 1975	1 01 00														27 OCT 300
27 OCT 1975	1 01 00														28 OCT 301
28 OCT 1975	1 01 00														29 OCT 302
29 OCT 1975	1 01 00														30 OCT 303
30 OCT 1975	1 01 00														31 OCT 304
31 OCT 1975	1 01 00														1 NOV 305
1 NOV 1975	1 01 00														2 NOV 306
2 NOV 1975	1 01 00														3 NOV 307
3 NOV 1975	1 01 00														4 NOV 308
4 NOV 1975	1 01 00														5 NOV 309
5 NOV 1975	1 01 00														6 NOV 310
6 NOV 1975	1 01 00														7 NOV 311
7 NOV 1975	1 01 00														8 NOV 312
8 NOV 1975	1 01 00														9 NOV 313
9 NOV 1975	1 01 00														10 NOV 314
10 NOV 1975	1 01 00														11 NOV 315
11 NOV 1975	1 01 00														12 NOV 316
12 NOV 1975	1 01 00														13 NOV 317
13 NOV 1975	1 01 00														14 NOV 318
14 NOV 1975	1 01 00														15 NOV 319
15 NOV 1975	1 01 00														16 NOV 320
16 NOV 1975	1 01 00														17 NOV 321
17 NOV 1975	1 01 00														18 NOV 322
18 NOV 1975	1 01 00														19 NOV 323
19 NOV 1975	1 01 00														20 NOV 324
20 NOV 1975	1 01 00														21 NOV 325
21 NOV 1975	1 01 00														22 NOV 326
22 NOV 1975	1 01 00														23 NOV 327
23 NOV 1975	1 01 00														24 NOV 328
24 NOV 1975	1 01 00														25 NOV 329
25 NOV 1975	1 01 00														26 NOV 330
26 NOV 1975	1 01 00														27 NOV 331
27 NOV 1975	1 01 00														28 NOV 332
28 NOV 1975	1 01 00														29 NOV 333
29 NOV 1975	1 01 00														30 NOV 334
30 NOV 1975	1 01 00														1 DEC 335

S=SUNSET/SUNRISE
 T=TWILIGHT
 *SPECCULAR REFLECTION AT SITE
 L=RECEIVED BY EARTH
 X=ALTITUDE LESS THAN 0 U.S.

Fig. 15. Specular reflection visibility chart (change in orbital inclination of 0.5°)

9 2422

SOI LCLITL GRAPHIC TIME TABLE
FROM SEP 1975 THROUGH NOV 1976

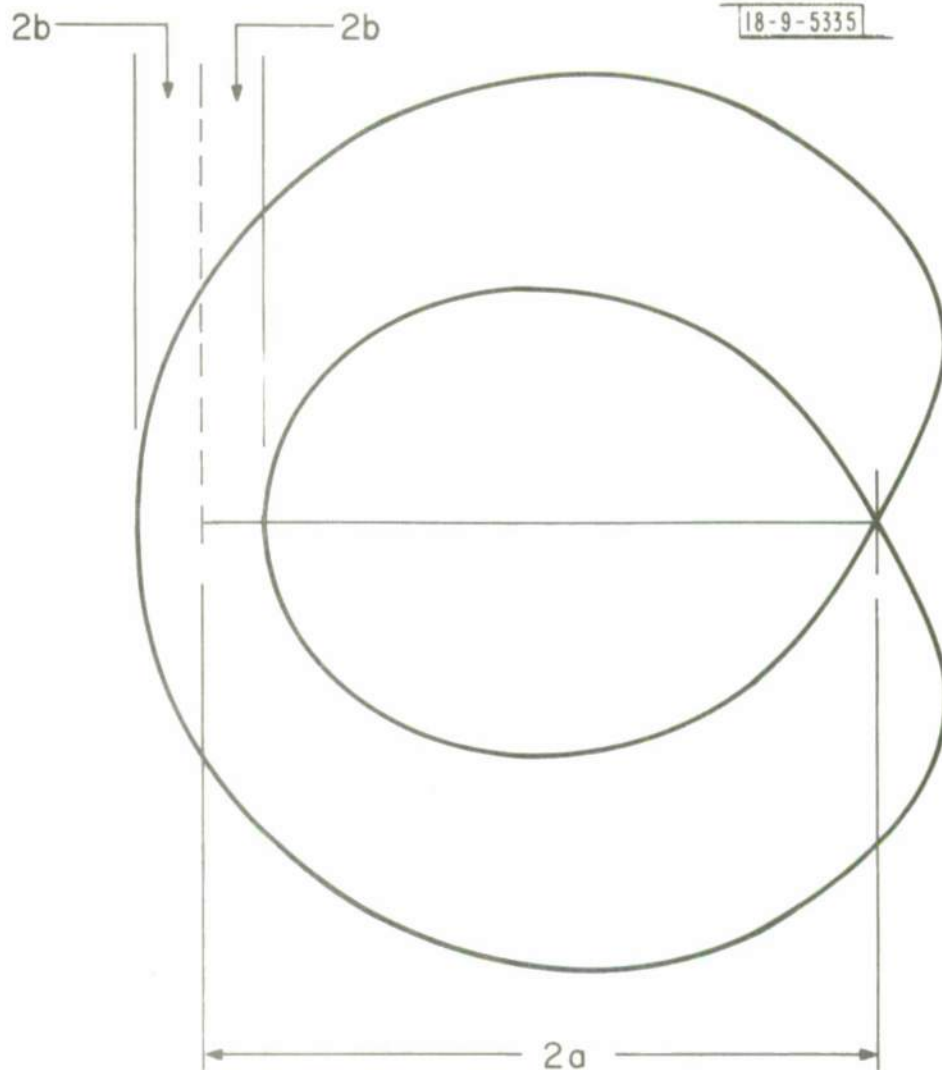
[illegible]

Fig. 16. Specular reflection visibility chart (change in satellite attitude of 0.2°)

periods available. In either case, the program facilitates tentative parameter modification, so that alternate predictions may be obtained for comparison.

The case of the wobbling satellite deserves further comment. As the satellite spins about a fixed axis, its symmetry axis revolves about that spin axis because of their misalignment. As a result, the geometric requirements for specular reflection may be satisfied during some portions of a spin period and unsatisfied during others. The relevant concept is the envelope of all specular rays which may periodically be reflected. This envelope is closely related to the classical limaçon of Pascal (cf. Figure 17) and can be described by a closed parametric formula. The shape of the resulting envelope is approximated in Figure 18. It still resembles a thickened cone, but the thickening is uneven and depends upon the amount of misalignment. Figure 19 shows our standard example with an introduced misalignment of 0.5° . Figure 20 shows a less artificial example, with orbital inclination of 5.7° , offset of 2.8° , and misalignment of 0.5° .

Extensive observations based on the above analysis are planned for the 1976 autumnal equinox. Already at hand are data from February and March, 1976, concerning Lincoln Experimental Satellite 6. LES-6 is particularly interesting because of its large misalignment of 2.2° and its unfavorable altitude at the Lincoln GEODSS site of less than 12° above the horizon. Pronounced specular returns were obtained at the times indicated in Figure 21, which are quite compatible with predicted



$$r = 2(b - a \cos \theta)$$

$$(x^2 + y^2 + 2ax)^2 = 4b^2(x^2 + y^2)$$

Fig. 17. Limaçon of Pascal

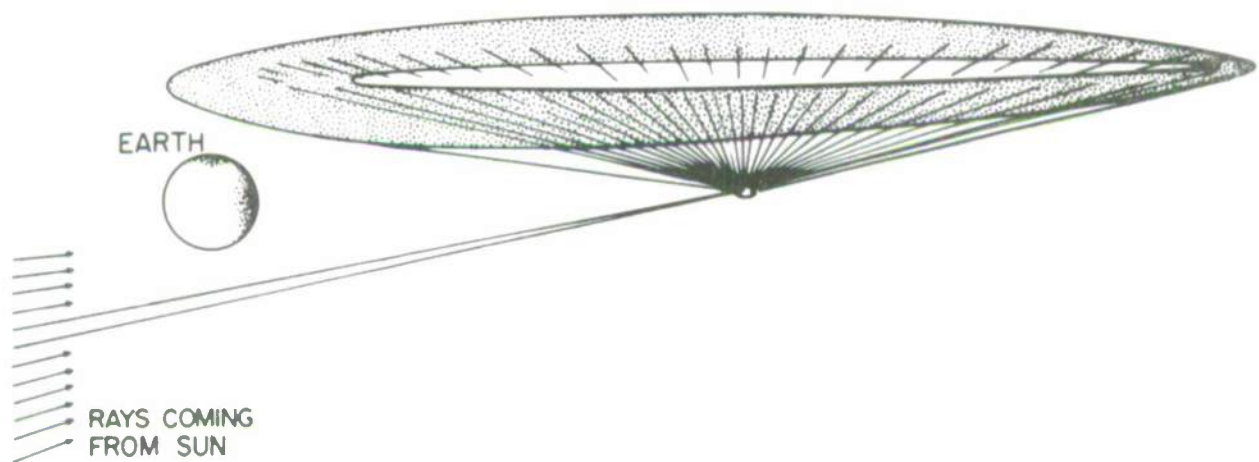


Fig. 18. Terrestrial visibility of solar specular reflection (wobbling satellite)

SPECULAR REFLECTION FROM CYLINDRICAL SATELLITE SPIN AXIS AND SYMMETRY AXIS MISALIGNED
 700000 USA SITE LASS
 UETTT HYPOTHETICAL GEOSTATIONARY SATELLITE

9-5421

EPOCHS 1976 245 01 01 0.0
 NS 1.002777777 AS 3.6105 LS 0.00000000 IS 0.0000
 ANOMALY 0.0000 AMPLITUDE 0.0000 MS 0.0000

MAGNITUDE 1.00 MAX 0.00 DECA 94.00 MISALIGNMENT 0.50
 OFFSET FROM ORB NUMERALS 0.00 LONG FROM ANOMALY 0.00

SATELLITE GRAPHIC TIME TABLE
 FROM SEP 1976 THROUGH NOV 1976

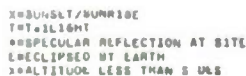
	16	17	18	19	20	21	22	23	S	1	2	3	4	5	6	7	8	
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1 SEP 245																		1 SEP 245
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28 NOV 334																		29 NOV 334
29 NOV 335																		30 NOV 335
30 NOV 336																		1 DEC 336
UNIVERSAL TIME																		

0.50 SUNSET/SUNRISE
 1.00 TWILIGHT
 0.50 SPECULAR REFLECTION AT SITE
 0.50 ECLIPSE AT 0.50
 0.50 ALTITUDE LESS THAN 0.50

Fig. 19. Specular reflection visibility chart (misalignment of 0.5° introduced)

-9-5420

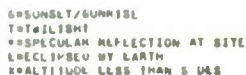
SATELLITE GRAPHIC TIME TABLE
FROM SEP 1978 THROUGH NOV 1976



27

4-5419

SATELLITE GRAPHIC TIME TABLE
FROM FEB 1976 THROUGH APR 1976



28

timing. A record of unsuccessful observation attempts for similar comparison would have been most desirable and will be included in the fall observing program.

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